Space and Remote Sensing Sciences Group Los Alamos National Laboratory Los Alamos, NM 87545, USA

1 Introduction

Advantages of ideal imaging FTS's:

- Spectral resolution can be varied easily by changing mirror scan path length and is usually much better than for a similar size dispersive instrument.
- High light throughput leads to improved signal to detector background ratio.
- Because the radiance spectrum is real the interferogram is an even function which allows using only one-sided interferograms, thus reducing the data storage requirements.
- 2-d image of scene is acquired allowing analysis of moving objects in the scene.

Problems of ideal imaging FTS's:

- Larger photon background noise because all light from a spectral region falls on the detector.
- Large dynamic range requires a large number of digitization levels.

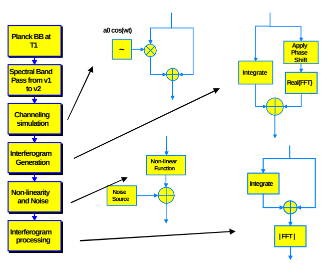
Problems with real imaging FTS data:

- Lenses, filters and beam splitter (sometimes also electronic amplifiers) introduce phase errors due to frequency dependent path differences which result in a broadening of the center-burst. Because the center-burst of a FTS with phase errors is in general asymmetric, full two-sided interferograms need to taken. Dispersion also reduces the dynamic range thus requiring fewer quantization levels [Griffiths and de Haseth].
- Pointing jitter smears out spatial information and can introduce unwanted spectral features.
- Internal reflections within the detector cause secondary ghosts (channeling) of the center-burst to appear in the spatial or interferogram domain
- Non-linear detector response causes harmonics to appear in the spectral domain
- Dead or noisy pixels must be corrected before jitter can be removed.

Solutions to real-world problems:

- Phase corrections using complex FFT's reduce the broadening of the center-burst.
- Correlation of flat-fielded frames of interferogram cube with a reference frame determines x/y shifts which can then be used to re-sample the image cube.
- Mask the channeling out before performing the Fast Fourier transform (FFT) to reduce the ringing.
- Correct the measured data by applying the inverse of the non-linear detector model to minimize spectral harmonics.
- Use bad pixel detection algorithms and morphologic image operators to interpolate values over bad pixels.

2 A flexible FTS model



Parameters for simulation:

- 3 calibration sources at temperatures $T_0 = 20C, T_1 = 30C$ and $T_2 = 40C$, signal to noise ratio $SNR = 1000$, number of samples $N_f = 4096$ frames, and a responsivity between 750 and 1250 cm^{-1}.
- Phase dispersion model: $\phi(\nu) = 500(\frac{\nu}{\nu_{max}})[1 + 0.3(\frac{\nu}{\nu_{max}})^2]$
- Channeling amplitude: $amplitude(\nu) = (1. + 0.2\cos(\omega_0 \nu))$
- Non-linear model: $DN(nonlin) = DN(lin)^d$ where $d = 0.33$

Task: Simulate the effect of phase errors, channeling and non-linearity on the 2-point calibration error on the measured black body (BB_1) using (BB_0) and (BB_2) measurements.

2.1 Two-point calibration

Let $I_k(x, i, j)$ be the interferogram of the k-th calibration source at T_k. Let's define the measured spectral response (MSR) at the (i, j) pixel as:

$$MSR_k(\nu, i, j) = |FFT[I(x, i, j)]|$$

. Given Planck's function $B()$, the calculated BB radiance for T_k is $CBB_k(\nu) = B(\nu, T_k)$. Assuming a linear detector the calibrated radiance $L_1(\nu)$ of BB_1 is:

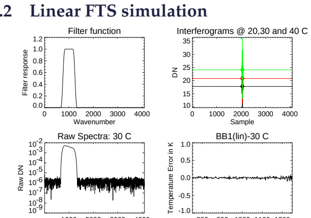
$$L_1(\nu) = \frac{MSR_1 - a(\nu, i, j)}{b(\nu, i, j)}$$

where

$$a(\nu, i, j) = MSR_0(\nu, i, j) + b(\nu, i, j)CBB_0(\nu), \text{ and}$$

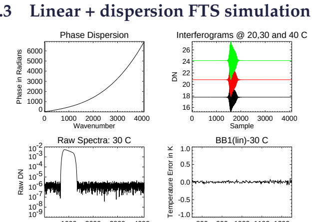
$$b(\nu, i, j) = \frac{MSR_2(\nu, i, j) - MSR_0(\nu, i, j)}{CBB_2(\nu) - CBB_0(\nu)}.$$

2.2 Linear FTS simulation



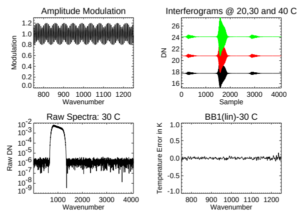
Note: The strongly peaked symmetric center-burst which allows the acquisition of one-sided interferograms.

2.3 Linear + dispersion FTS simulation



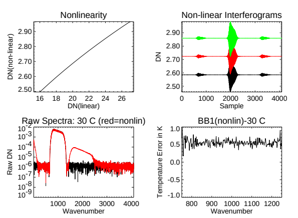
Note: The spread-out center-burst is no longer symmetric anymore, thus two-sided interferograms need to be taken. Also the dynamic range is reduced compared to the non-dispersed FTS.

2.4 Linear + dispersion + channeling FTS simulation



Note: Channeling causes ghosts of the center-burst. In the spectral domain the channeling manifests itself as amplitude modulations.

2.5 Non-linear + dispersion + channeling FTS simulation



Note: The spectral harmonics occur at the sum and differences of the in-band wavenumbers. There is a corresponding non-zero mean temperature offset on BB_1 and increased temperature noise compared to linear FTS's.

3 Radiometric corrections

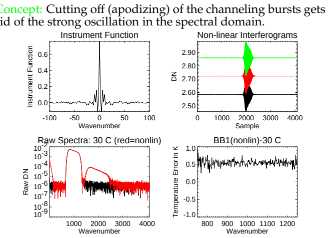
3.1 Phase error correction

Concept: Using a phase estimation technique it is possible to convert a dispersed interferogram into a non-dispersed interferogram.

Note: Experience with FTS data shows that there is usually only a small improvement of SNR (theoretical improvement is $\sqrt{2}$) if a phase correction is performed.

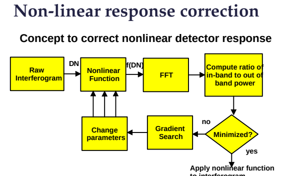
3.2 Channeling effect correction

Concept: Cutting off (apodizing) of the channeling bursts gets rid of the strong oscillation in the spectral domain.



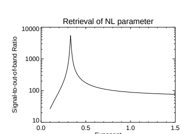
Note: Removing channeling eliminates the sinusoidal modulation in the spectral domain. Removing the channeling, however, introduces instrument functions with side lobes (see figure) which introduce ringing near narrow spectral features, i.e. atmospheric absorption lines.

3.3 Non-linear response correction



Retrieval of the exponent d uses the ratio

$$R = \frac{max\{in - band \ Signal\}}{\sigma\{Out - of - band \ Signal\}}.$$



Note: The exponent 0.33 was correctly identified.

4 Geometric corrections

Problem: Given a reference image $I(0)$ and a sequence of N x/y shifted and rotated images find the optimal shifts, $x_{opt}(n)$ and $y_{opt}(n)$ and rotation, $\phi_{opt}(n)$, to minimize:

$$RMSE(I(0) - rotate(shift(I(n)), x_{opt}(n), y_{opt}(n)), \phi_{opt}(n))).$$

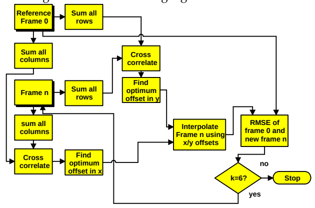
Possible Algorithms:

1. Direct 3-D cross correlation to find x/y shifts and rotation.
2. Direct 2-D cross correlation to find x/y shifts
3. Adaptive (from low resolution to high-resolution) 2-D image correlation
4. Reduce problem to separable 1-D correlations to also handle rotations

Advantages of 4 over 1-3: Perform simple 1-D correlations rather than computationally expensive 2 or 3-dimensional. Methods 2 and 3 only work for shifts.

4.1 Fast x/y shift determination

Block diagram for a fast tracking algorithm:



Steps:

1. Initialize a maximum search range R_0, e.g. +/- 5 pixels
2. Sum over all rows and columns of reference frame to obtain 1-D vectors $S_x(0) = \sum_x (I(0))$ and $S_y(0) \sum_y (I(0))$.
3. For frame n and k iterations do:
   (a) Let $x_{opt,0}(n) = x_{opt}(n-1)$ and $y_{opt,0}(n) = y_{opt}(n-1)$
   (b) Cross-correlate 1-D vectors over a range of shifts from $-R$ to R in 11 steps:

$$S_x(n) = \sum_x (shift(I(n), x_{opt}(n-1), y_{opt}(n-1))), \text{ and}$$

$$S_y(n) = \sum_y (shift(I(n), x_{opt}(n-1), y_{opt}(n-1)))$$

   with $S_x(0)$ and $S_y(0)$ to find residual shifts δ_x and δ_y which minimize $RMSE(S_x(0) - shift(S_x(n), \delta_x, \delta_y))$ and $RMSE(S_y(0) - shift(S_y(n), \delta_x, \delta_y))$.
   (c) Let $x_{opt,k}(n) = x_{opt,k-1}(n) - \delta_{x,k-1}$ and $y_{opt,k}(n) = y_{opt,k-1}(n) - \delta_{y,k-1}$
   (d) Reduce the range by $R_k = R_{k-1}/2$

4.2 Fast rotation determination

Steps:

1. Initialize a maximum search angle range for Φ_0, e.g. +/- 5 degrees
2. Sum over all rows and columns of reference frame to obtain 1-D vectors $S_x(0) = \sum_x (I(0))$ and $S_y(0) \sum_y (I(0))$.
3. For frame n and k iterations do:
   (a) Let $\phi_{opt,0}(n) = \phi_{opt}(n-1)$
   (b) Cross-correlate 1-D vectors over a range of angles from $-\Phi$ to Φ in 11 steps:

$$S_x(n) = \sum_x (rotate(I(n), \phi_{opt}(n-1))), \text{ and}$$

$$S_y(n) = \sum_y (rotate(I(n), \phi_{opt}(n-1)))$$

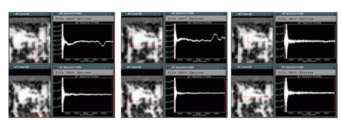
   with $S_x(0)$ and $S_y(0)$ to find residual rotation angle $\delta\phi$ which minimize $RMSE(S_x(0) - rotate(S_x(n), \delta\phi)$.
   (c) Let $\phi_{opt,k}(n) = \phi_{opt,k-1}(n) - \delta\phi_{k-1}$
   (d) Reduce the angular range by $\Phi_k = \Phi_{k-1}/2$

4.3 Effect of jitter

Effect of jitter depends on the surrounding area:

- A bright pixel surrounded by dark pixels shows strong base line shifts
- A dark pixel surrounded by dark pixels shows strong base line shifts
- A pixel in a uniform region shows no baseline shifts

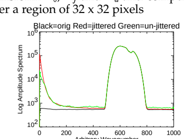
Effect of Jitter Restoration on Pixels near Contrasts (a,b) and in uniform Regions (c) shown in the FTIR data cube



(a) Bright Pixel | (b) Dark Pixel | (c) Uniform Pixel

Experiment Steps:

1. Generate a simulated linear FTS image cube C_0 and jitter each frame of the cube using a known jitter function $x_{off}(n)$ and $y_{off}(n)$ to obtain a cube C_j.
2. Perform un-jittering of cube and store result in C_u.
3. Fourier transform C_0, C_j and C_u and compute the average spectra over a region of 32 x 32 pixels

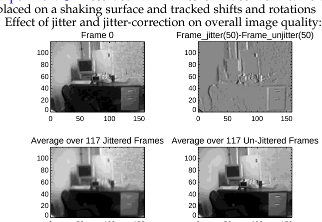


Notes: The un-jittering process has little effect on the spectral region of interest (500-800 arbitrary wavenumbers) but reduces the spurious signal near zero wavenumber.

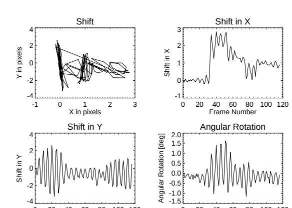
4.4 Results

Experiment 1: Recorded 117 frames of video from camera placed on a shaking surface and tracked shifts and rotations

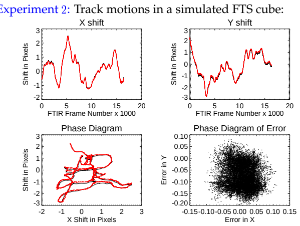
Effect of jitter and jitter-correction on overall image quality:

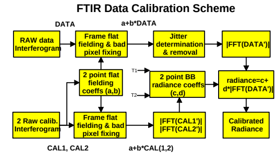


Results of tracking for video sequence:



Experiment 2: Track motions in a simulated FTS cube:





Additional processing:

Frame flat fielding: There may be residual stripes in each frame for the CAL and DATA cubes which need to be removed before cross-correlations are performed for jitter removal

Bad pixel fixing steps:

1. Find "bad pixels"="dead" pixels and "noisy" pixels
2. Grow a region around "bad pixels" using a cross shaped kernel
3. Delauney triangulation of neighbor pixels and quintic interpolation at bad pixels

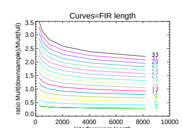
5 Data compression

Facts:

- System spectral response is usually band limited (e.g. 8-12 μm band).
- Only a fraction (1/8 th) of the spectral image cube is retained after the FFT which is a $N \log N$ complex operation.

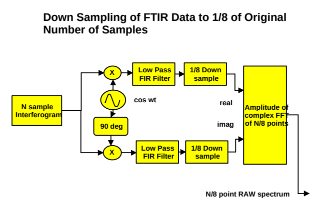
Example: Compute ratio of the number of multiplications required for a reduced FFT with down-sampling over the number required for a full FFT a function of interferogram length N and finite-impulse-response (FIR) length L:

$$R = \frac{N/8 \log_2 N/8 + 2N/8L}{N \log_2 N}.$$



Problem: Find a solution to reduce the amount of operations to generate the spectral cube and save storage space for the raw data.

Solution: Modulate the interferogram and low-pass filter with a super-heterodyne receiver.



6 Conclusions

Several "real world" effects on FTS data have been presented and some methods to reduce their effect:

- Channeling can be removed by apodizing the interferogram with the penalty of introducing ringing near spectral lines or calibrated out given a sufficiently stable FTS system.
- Jitter removal improves image sharpness but has little effect on spectral fidelity if the jitter is low-frequency.
- Non-linearity corrections eliminate systematic calibration errors.
- Super-Heterodyne processing reduces the amount of operations to generate the spectral cube and storage requirements.

7 References

- Beer, R., Remote sensing by Fourier transform spectrometry, Fourier transform spectroscopy, Remote Sensing. xvii, 153 p., New York, N.Y., Wiley, 1992.
- Peter R. Griffiths and James A. de Haseth, Fourier transform infrared spectrometry, xv, 656 p., New York, Wiley, 1986.
- Bennett, C.L., LIFTRS, the Livermore imaging FTIR, Conference on Fourier transform spectroscopy, 11., p.170-186, 10-15 Aug, 1997. Online at: http://www.llnl.gov/tid/lof/documents/pdf/231514.pdf
- A very nice introduction in French to Michelson interferometers can be found at: http://www.sciences.univ-nantes.fr/physique/enseignement/tp/michelson/michp.html
- A nice write-up by Paul Van Delst on correcting HgCdT non-linearities for the AERI instrument can be found at: http://airs2.ssec.wisc.edu/~paulv/aeri/aerinsa_nlanalysis/971113b1/971113b1.html
- Software to perform jitter correction using a hierarchical cross-correlation technique can be found at: http://idlastro.gsfc.nasa.gov/ftp/contrib/varosi/vlib/
- The PostScript version of this poster will be available on: http://nis-www.lanl.gov/~borel